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Why should standard eddy-current distortion correction techniques be avoided even for moderately high b-value data?

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PURPOSE This work highlights issues with the current practice for correcting eddy-current distortions on moderately high b-value data, and demonstrates their mitigation with a simple alternative. In recent years there has been a shift from the acquisition of data at standard b-values (~1000s/mm^2) to moderately high b-values (2000-3000s/mm^2) in order to obtain information on specific microstructural features [1] or departures from Gaussian diffusion [2]. As higher b-values lead to more pronounced eddy-current (EC) artefacts, accurate estimation of novel microstructural features depends on having available techniques that can cope with larger distortions. The standard correction technique, registration of diffusion-weighted images to the b=0, is known to fail at very high b-values [3] but has remained the routine practice for datasets with moderately high b-values. Here we demonstrate that the standard approach provides questionable correction even for this increasingly common class of data, and show this can be improved upon with a technique designed to function well regardless of a dataset's b-value [4]. Both techniques are evaluated on real and simulated data, and the importance of EC correction for estimating microstructure is illustrated with the NODDI model.

METHODS Simulation: One shell of DWIs with 64 directions and b=2000s/mm^2 was generated using POSSUM [5], both with and without EC distortions. Rician noise was added to give an SNR of 20 (for b=0). Data: Diffusion data was acquired on two healthy volunteers using a 3T Siemens system according to the two-shell NODDI protocol [1]: TE/TR = 103/7500ms, δ/Δ fixed, 32 directions with b=700s/mm^2, 64 with b=2000s/mm^2 and 12 b=0. Standard correction: We used the eddy_correct tool in FSL 5 to represent the common practice of registering each DWI to the first b=0. Proposed alternative: The method in [4] avoids registration to the b=0 by exploiting the fact that the EC distortions, which are a function of the applied diffusion gradients, can instead be determined by pairwise registration between DWIs with similar contrast. Furthermore, to account for the dependence of EC distortion on slice position, the distortions are parameterized with 2-D transformations and estimated slice-wise. An in-house Matlab implementation of this method was used. Assessment: Correction of simulated data was assessed by comparing each image to its counterpart generated without EC distortions. Assessment of real data followed the standard approach in the literature: the comparison of DWIs to an outline drawn on the undistorted b=0 image. The impact of the quality of EC correction was investigated by fitting datasets to the NODDI model and examining fitting errors.

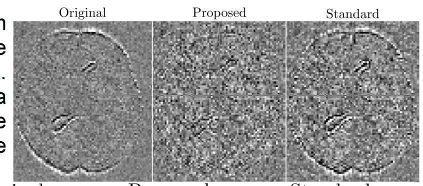

Fig. 1: Differences from ground truth for one slice of the simulated dataset. Shown for original data and data corrected by the proposed and the standard schemes.

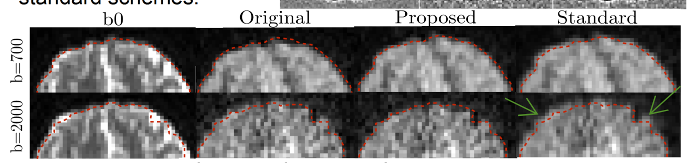

Fig. 2: Examples of data before and after correction. Red outlines were drawn around an undistorted b0. Over-scaling highlighted by green arrows.

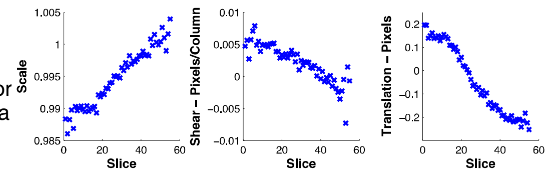

Fig. 3: The estimated correction parameters for each slice of a DWI from the proposed scheme.

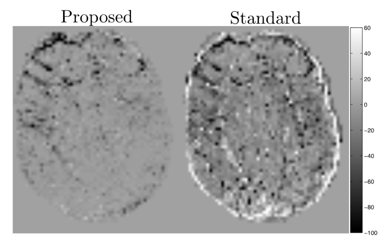

Fig. 4: The *difference* in NODDI fitting errors between the original and corrected datasets: original - corrected. The dark regions signify smaller errors in the corrected dataset. The white rim around the data corrected with the standard scheme is consistent with its noted tendency to over-scale the data.

RESULTS & DISCUSSION Eddy correction comparison Experiments on simulated and real data show that the standard technique was able to correct distortions in the b=700 shell but not the b=2000 shell, whilst the proposed alternative was able to correct both shells. Simulations (Fig 1) show that the standard approach offered partial correction at best, and sometimes led to worse alignment than seen in the uncorrected data, whilst the proposed method gave good correction. Results on real data (Fig 2) support this finding, and in particular they make it clear that the standard approach systematically over-scales the DWIs in the b=2000 shell. Intra-volume variation Figure 3 shows the clear dependence of EC distortion on slice position and emphasizes the importance of accounting for this effect. The estimated correction, parameterized in terms of shear, scaling and translation along the phase-encoding direction [6], varies with slice position within each DWI. These variations are important because they are enough to cause offsets of more than one voxel between the first and last slices but the standard approach, which estimates a single transformation for each DWI, cannot capture this effect. Model fitting performance Figure 4 shows that the standard approach results in questionable model fitting that the proposed scheme avoids. The standard technique had larger fitting errors than the uncorrected dataset in many regions. The poor fitting is most noticeable in the strong white rim around the brain, which is caused by over-scaling of the DWIs so that they lie outside the brain's boundary as defined by the b=0 images. This poor anatomical correspondence between the b=0 and DWIs will adversely impact any microstructural measurements made with such data.

CONCLUSIONS This work demonstrates that correcting moderately high b-value data with standard EC correction techniques introduces distortion that compromises the anatomical correspondence between the DWIs and leads to questionable estimates of microstructural features. We further show how to circumvent these issues with a simple alternative. FSL's new eddy tool provides another potential alternative, but we did not evaluate it here because it requires an uncommon sampling scheme.

REFERENCES 1. Zhang et al, NeuroImage 2012 **2.** Hanzhang et al, NMR in Biomedicine **3.** Bastin, MRI 1999 **4.** Zhuang et al, JMR 2013 **5.** Drobnjak et al, MRM 2006 **6.** Jezzard et al, MRM 1998